Semi-inclusive deep inelastic lepton scattering on nucleons and nuclei

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Chapter 1

Introduction

Inclusive deep inelastic lepton scattering on nucleons is a well established tool for the investigation of the quark-parton model. In the Bjorken limit the cross section is proportional to a structure function which depends on only one scaling variable x, that can be interpreted as the light-cone momentum fraction of the hit quark. Deep inelastic scattering on nuclear targets showed [1–3] that the x distribution of quarks in nucleons bound in a nucleus differs from the one for a free nucleon (EMC effect). While part of this effect can be explained in terms of nuclear binding and fermi motion [4–6] there is evidence that additional, possibly non-nucleonic, effects are required to obtain agreement with the data. However, since in inclusive experiments one averages over all, strongly and weakly bound, nucleons it is not possible to draw definite conclusions about the nature of these effects.

More detailed information on the deep inelastic scattering process can be obtained from more exclusive experiments. In this thesis we study semi-inclusive deep inelastic scattering on nucleons and nuclei in which at least one slow (i.e. low energy) proton is detected in coincidence with the scattered lepton.

This research was triggered by the publication of the results of neutrino induced deep inelastic scattering experiments at Fermilab (E745 Collaboration) [7, 8] and at CERN (BEBC Collaboration) [9]. In these experiments events were characterized by the presence (or absence) of short ionized tracks at the interaction vertex (sometimes referred to as 'dark tracks' or 'stubs'). The latter were identified as slow protons with a momentum below approximately 1 GeV/c.

It was observed that events with and without a slow proton in the final state exhibit a different x behaviour. This is reflected in the ratio of the structure function of a bound and a free nucleon (EMC ratio): the dip at intermediate x (which is usually attributed to the binding of the nucleon) is larger for events with dark tracks than for events without [7–8, 10]. Using a mean-field approach it was argued that the events with a slow proton in the final state originate from the absorption of the virtual boson by a deeply bound nucleon whereas the events without dark tracks correspond to the scattering off loosely bound nucleons located at the surface of the nucleus [7, 11]. However, the binding model of deep inelastic scattering cannot explain the production of backward protons without the inclusion of nuclear correlations.

There are several reasons why the semi-inclusive scattering process is of interest both on a free nucleon and on nuclear targets.

Nucleon targets

On a free nucleon slow protons originate from hadronization of the spectator quarks in the struck nucleon (so-called target fragmentation). In Refs. [12–13] semi-inclusive deep inelastic scattering on a free proton was considered, assuming factorization of the cross section into a structure function $F(x)$ and a spectator quark (debris) fragmentation function $D(\alpha)$, where α is the light-cone momentum fraction carried by the observed proton. It was found that the ratio $P(x, \alpha)$ of the semi-inclusive cross section $\sigma(x, \alpha)$ and the inclusive cross section $\sigma(x)$ has a strong bias for small x values (in agreement with experiment). Qualitatively this behaviour can be explained by kinematics: a proton at rest in the target rest system can only be produced at $x = 0$; on the other hand the dependence on α and some details of x dependence are sensitive to the shape of the fragmentation function.

An interesting process to study the fragmentation of a neutron into a slow proton in (anti-)neutrino induced reactions. In a pure valence quark approach the cross section for $\bar{\nu} + n \to \mu^+ + p + R$ would almost vanish. However, in practice one must also take into account sea-quark contributions which are important at small x.

The latter can be treated in two ways, namely as a 4-quark fragmentation or as a bag of valence quarks surrounded by a pion cloud, which is struck by the lepton. While these models give similar results for inclusive processes there are interesting differences for exclusive reactions. For example, in the pion model one can produce slow protons in $\bar{\nu} + n$ in two ways: via $n \to p + \pi^-$, and via $n \to \Delta^0 + \pi^0$ with subsequent decay of the isobar into $p + \pi^-$, whereas in the naive leading order 4-quark fragmentation only the latter process contributes to the production of slow protons.

Deuteron target

The simplest nuclear target for studying semi-inclusive deep inelastic processes is the deuteron. On nuclear targets there are several mechanisms that can give rise to slow protons. First there is the above mentioned debris fragmentation of the quarks in the struck bound nucleon, giving rise to creation of new particles and possible change of momenta of spectator nucleons. From a comparison with the free nucleon one obtains information on the effects of the nuclear medium on the hadronization process.

Another category of slow protons in deep inelastic scattering on nuclei are spectator nucleons which are emitted as a result from nucleon-nucleon correlations present in the target ground state. In the special case of the deuteron the light-cone momentum fraction α of an observed spectator proton directly determines the light-cone momentum fraction of the nucleon being struck by the lepton, $y \approx 2 - \alpha$. In this case one deals with the tagged EMC effect (originally proposed by Frankfurt and Strikman [14]). This is of interest since it might help to determine whether the convolution approach to the EMC effect is appropriate [5, 15], or that non-nucleonic degrees of freedom are required [16, 17].

Whereas in scattering on a free nucleon the direct hadronization process is the only one possible, in nuclei both the direct and spectator processes occur and it is of interest to investigate their characteristic behaviour. To this end the double differential cross section $\sigma(x, \alpha)$ for the production of slow protons with light-cone momentum fraction α is calculated. For the experimental data the result of a recent new analysis of the WA25 collaboration is used. In the latter a (partial) decomposition of the (anti-)neutrino semi-inclusive cross section is achieved in terms of spectator, direct and rescattering events. In particular the spectator contribution can be uniquely identified by sampling the slow protons in the backward hemisphere. Thus it allows one to compare the various processes separately with experimental results.

Also of interest are the possible effects of final state interactions. After hadronization of the quarks in the hit nucleon (which is determined by the formation time) the hadrons which are produced in forward direction can in general interact with the spectator nucleons and thus lead to a possible modification of their momentum distribution and charge and the creation of new particles. The possibility to study the dependence of rescattering on the formation (hadronization) time is of interest since it plays an essential role in the interpretation of heavy ion reactions.

Nuclear targets with $A > 2$

For a general nuclear target the basic processes contributing to the production of slow protons are the same as those for the deuteron. In case of the hadronization of the struck nucleon the main difference lies in the larger Fermi momentum and binding energy of the nucleons. The calculation of the spectrum of emitted spectator nucleons is complicated by the center-of-mass motion of the correlated pair of nucleons. Finally, due to the larger size of the nucleus, rescattering will play a more important role than in the case of the deuteron.

Outline

This thesis is organized as follows. In Chapter 2 a general introduction to the formalism for semi-inclusive deep inelastic scattering on nucleons is presented. Using this formalism, general expressions for the semi-inclusive structure functions and cross sections are given in terms of quark momentum distributions and fragmentation functions.

In Chapter 3 the cross sections for semi-inclusive scattering on a nucleon are calculated using phenomenological fragmentation functions as well as a pion-nucleon model. The results are compared with experimental data.

In Chapter 4 the cross sections for semi-inclusive scattering on nuclei are calculated. Included are scattering and subsequent hadronization off a bound nucleon and the emission of nuclear spectators. Furthermore, the role of final state interactions is discussed.

In Chapter 5 this formalism is applied to the deuteron, and the results are compared with experimental data.

Finally, in Chapter 6 we summarize and discuss the results. Also we propose a number of experiments to clarify some of the ambiguities in the present data.

Most of the material presented in this thesis has been published in Refs. [12, 13, 18, 19]